

# Swift observations of SAX J1808.4–3658: monitoring the return to quiescence

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## ABSTRACT

The transient accreting millisecond pulsar SAX J1808.4–3658 has shown several outbursts to date but the transition from outburst to quiescence has never been investigated in detail. Thanks to the Swift observing flexibility, we monitored for the first time the decay to quiescence during the 2005 outburst. At variance with other transients, wide luminosity variations are observed. In addition, close to quiescence, SAX J1808.4–3658 seems to switch between two different states. We interpret them in terms of the accretion states accessible to a magnetized, fast rotating neutron star.

*Subject headings:* accretion, accretion disks — star: individual (SAX J1808.4–3658)  
— stars: neutron

## 1. Introduction

SAX J1808.4–3658 (SAX J1808 in the following) was the first neutron star transient during whose outbursts coherent pulsations were detected (Wijnands & van der Klis 1998). This source, together with six other low mass transients (see Wijnands 2005 for a review), form a separate (sub-)class within neutron star transients (see Campana et al. 1998a for a review). Distinctive properties, besides coherent pulsations, are weaker outburst peak luminosities ( $\sim (1-5) \times 10^{36}$  erg s<sup>-1</sup>), very low mass companions (mass functions  $< 2 \times 10^{-3} M_{\odot}$ ), short orbital periods ( $P_{\text{orb}} \lesssim 4.3$  hr), very faint quiescent luminosities ( $\lesssim 5 \times 10^{31}$  erg s<sup>-1</sup>) and absence of a soft X-ray spectral component in quiescence.

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A further difference with respect to ‘classical’ neutron star transients concerns the return to quiescence following an outburst. The best light curve to date of ‘classical’ neutron star transients is represented by BeppoSAX observations of Aql X-1 (Campana et al. 1998b). Below a luminosity level of  $\sim 10^{36}$  erg s $^{-1}$  Aql X-1 turned off with an exponential decay with an  $e$ -folding time of  $\sim 1$  d. The source then remained quiescent for at least one month following the 1998 outburst (Campana et al. 1998b) and for five months following the 2000 outburst (Rutledge et al. 2001; Campana & Stella 2003). The return to quiescence for transient pulsating neutron stars has been monitored for SAX J1808 (Wijnands et al. 2003; Wijnands 2005) and for XTE J1751–305 (Markwardt et al. 2002) and Swift J1756.9–2508 (Krimm et al. 2007). The behaviour of the latter two sources was somewhat similar to Aql X-1 with a fast decay, even though in the case of XTE J1751–305 there was still activity 15 d after the transition to quiescence had occurred (according to RXTE/PCA, corresponding to a 0.5–10 keV unabsorbed luminosity of  $\sim 10^{35}$  erg s $^{-1}$  for a source distance of 7 kpc). In case of SAX J1808 the decay was completely different from that observed in Aql X-1. The most striking feature is the strong erratic variability by a factor of  $\gtrsim 30$ . This erratic behaviour was not concentrated in the first few weeks after turn off but lasted for months (e.g. Wijnands et al. 2004). The most likely explanation for this behaviour comes from the similarities with dwarf novae where a similar behaviour has been observed (Kato et al. 2004; Patterson et al. 2002) and to a lesser extent in black hole transients (Kuulkers, Howell & van Paradijs 1996). In the case of dwarf novae this has been interpreted as due to a combination of short orbital period and low mass ratio (Osaki & Meyer 2002; Truss et al. 2002; Campana et al. 2008, in preparation).

Here we report on a monitoring campaign carried out with Swift, following the 2005 outburst. At variance with previous monitoring with RXTE/PCA we are able to follow the source down to very low levels, a factor of  $\sim 50$  fainter than before, close to quiescence. In Sect. 2 we discuss the data and their analysis. Sect. 3 contains our discussion and conclusions.

## 2. Data analysis

Swift carried out 23 observations of SAX J1808 between Jun 17, 2005 and Oct 28, 2005. XRT collected a total of 4899 s data in Window Timing (WT) mode and 72922 s data in Photon Counting mode (see Table 1). In WT mode a 1D image is obtained reading data compressing along the central 200 pixels in a single row. PC mode produces standard 2D images (for more details see Hill et al. 2004). WT data were mainly collected during the early stages of the outburst when the source was brighter. PC data collected during this period are piled-up.

The XRT data were processed with standard procedures (xrtpipeline ver. 0.11.6 within FTOOLS in the Heasoft package ver. 6.4), filtering, screening, and grade selection criteria (Burrows et al. 2005). For the WT data, we extracted source events in a square region with a side of 20 pix-

Table 1: Observation log.

Obs. ID.	Date (2006)	WT exp. time (s)	PC exp. time (s)	Count rate (c s <sup>-1</sup> )	Counts
00030034001	17 Jun	119	787	4.46	3510 (P)
00030034002	20 Jun	0	1061	1.49	1581 (P)
00030034003	23 Jun	761	206	3.01	620 (P)
00030075001	29 Jun	1043	0	4.09	4396
00030034005	07 Jul	866	0	8.14	7157
00030034006	13 Jul	733	394	3.10	1221 (P)
00030034010	02 Aug	0	416	8.88E-03	4 [A]
00030034011	05 Aug	0	1041	6.31E-03	7 [A]
00030034012	13 Aug	1028	2486	1.84	4574 (P)
00030034013	21 Aug	0	1675	9.05E-03	15 [A]
00030034014	28 Aug	68	1928	1.36	2622 (P)
00030034015	30 Aug	0	2550	6.26E-02	160
00030034016	31 Aug	0	2838	9.87E-03	28 [A]
00030034017	02 Sep	0	2084	5.48E-03	11 [A]
00030034018	14 Sep	0	9011	1.50E-03	14 [B]
00030034019	25 Sep	123	7329	6.47E-03	47 [A]
00030075020	30 Sep	42	4922	4.89E-03	21 [A]
00030034021	04 Oct	0	7757	1.74E-03	12 [B]
00030034020	11 Oct	0	2986	4.89E-03	15 [A]
00030034022	12 Oct	0	4689	1.64E-03	7 [B]
00030034023	16 Oct	0	6742	1.83E-03	12 [B]
00030034024	20 Oct	0	4736	<3.49E-03	16
00030034025	28 Oct	116	7284	<3.00E-03	22

Labels in the last column indicate: (P) piled-up photon counting data; [A] state A observation; [B] state B observation.

els. Ancillary response files generated with `xrtmkarf` and accounted for different extraction regions, vignetting, and point-spread function (PSF) corrections. In PC mode we extracted data with variable extraction regions depending on source strength, ranging from annular region with inner (outer) radius of 10 (40) pixels when the source was very bright, down to 10 pixel circular region when the source was very faint in order to increase the source signal vs. the background.

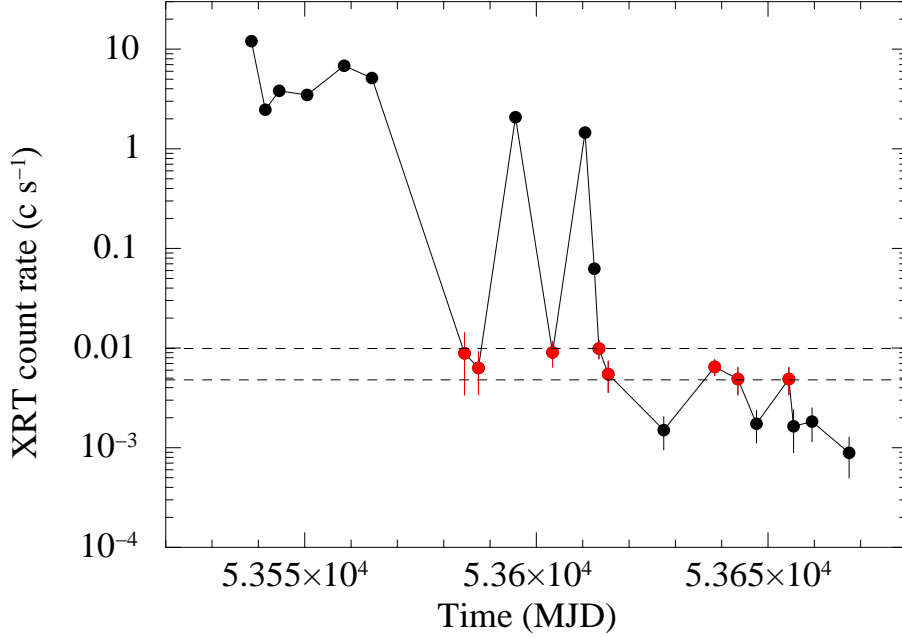


Fig. 1.— SAX J1808 light curve observed with Swift XRT during the 2005 outburst.

## 2.1. Outburst light curve

The first observations caught SAX J1808 during the latest stages of the outburst phase at a count rate level (corrected for pile-up) of more than  $10 \text{ counts s}^{-1}$ . Starting from MJD 53564 the source decreased its count rate by a factor of  $\sim 600$  in 20 days (unfortunately no observations were taken during this period due to the occurrence of number of gamma-ray bursts, see Fig. 1). Two observations within 3 days showed the source at a level of  $0.01 \text{ counts s}^{-1}$  well above the quiescent level. After this sharp decay, SAX J1808 entered a “flaring” behaviour (Wijnands et al. 2003; Wijnands 2005). Our data evidence that this activity lasted for about one month; after that the source returned to its quiescent state with some comparatively small scale variability (factor of  $\sim 5$ ) superimposed (see also below).

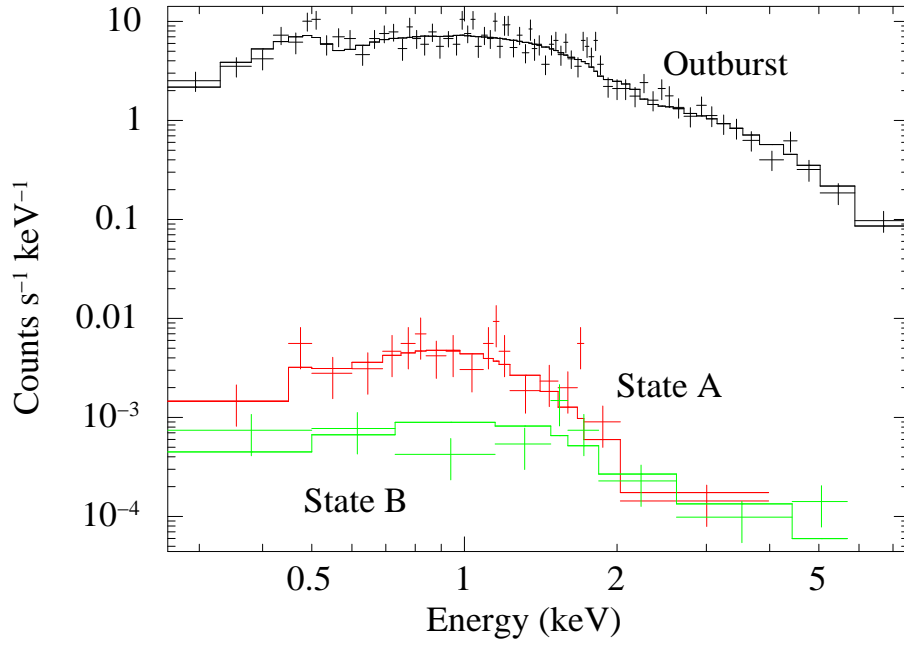


Fig. 2.— XRT spectra of SAX J1808.4–3658. The topmost spectrum is a representative of the outburst state. The middle spectrum refers to state A and the lowest one to state B (see text for more details). All spectra were fitted with an absorbed black body plus power law model.

## 2.2. Spectral analysis: bright end

We fit the entire data set with an absorbed black body plus power law model, keeping the same value of the column density for all the spectra. The best column density is  $(1.3 \pm 0.1) \times 10^{21} \text{ cm}^{-2}$  (90% confidence level, modelled with TBABS). In Table 2 we report the results of our spectral modelling. From this table and Figs. 2 & 3 it is clear that during the outburst decay and flaring period the power law photon index ( $\Gamma \sim 2.3$ ) and the black body temperature ( $kT \sim 0.65 \text{ keV}$ ) remained almost constant. This behaviour occurs in the (unabsorbed) 0.3–10 keV luminosity range of  $7 \times 10^{34} - 10^{36} \text{ erg s}^{-1}$  (i.e. a factor of  $\sim 15$ ), assuming a source distance of 3.5 kpc (Galloway & Cummings 2006).

## 2.3. Spectral analysis: faint end

At lower luminosities the number of collected photons is very small and we have to stack together different observations. One important consideration comes from the observation that 8 out of 13 observations found the source with a count rate in the narrow interval  $5 - 10 \text{ c ks}^{-1}$ , whereas the other 5 all lie within  $0.8 - 2 \text{ c ks}^{-1}$ . The mean of the first group is  $6.3 \pm 1.1 \text{ c ks}^{-1}$  and of the second is  $1.3 \pm 0.4 \text{ c ks}^{-1}$ . This is rather peculiar and hints for the existence of two different states in the deep faint end tail of the outburst. Due to the small number of photons these spectra can be easily fit with single power law models. For state A we derive a photon index of  $\Gamma = 2.7 \pm 0.3$  and a mean unabsorbed 0.3–10 keV luminosity of  $5.0 \times 10^{32} \text{ erg s}^{-1}$ , for state B we have  $\Gamma = 1.7 \pm 0.6$  and a luminosity of  $1.5 \times 10^{32} \text{ erg s}^{-1}$ . These values have been derived binning the data to 5 photons per energy bin and applying the Churazov weighting in the fitting procedure (see Fig. 2). This indicates that state B is not yet the true quiescent state, characterized by a single power law spectrum with index  $\Gamma = 1.93^{+0.37}_{-0.29}$  and a source luminosity of  $(5.2 \pm 0.1) \times 10^{31} \text{ erg s}^{-1}$  (Heinke et al. 2007), i.e. a factor of  $\sim 3$  smaller than state B luminosity. Assuming this power law component as a stable component (at least in photon index) present in state A and B spectra, one can investigate if a black body component is present. Fitting state A spectrum with a fixed power law photon index (with  $\Gamma = 1.93$ ) and a free black body component, we derive  $kT = 0.20 \pm 0.05 \text{ keV}$  and a radius of  $R = 1.3^{+0.3}_{-0.5} \text{ km}$ . The improvement over the simple power law fit is at a level of  $2.2 \sigma$  by means of an F-test. For state B we are not able to constrain the black body component. However, if we assume the same black body temperature as in state A (i.e. 0.2 keV) we can derive an upper limit on its radius of  $R < 0.3 \text{ km}$ , indicating that if present and at the same temperature it must be smaller in size.

Table 2: Spectral fits.

Date	BB Temperature (keV)	BB Radius (km)	PL index	Luminosity <sup>a</sup> (erg s <sup>-1</sup> )
2005-06-17 <sup>b</sup>	0.72 <sup>+0.13</sup> <sub>-0.13</sub>	2.3 <sup>+1.0</sup> <sub>-0.9</sub>	2.24 <sup>+0.15</sup> <sub>-0.11</sub>	1.0 × 10 <sup>36</sup>
2005-06-20 <sup>b</sup>	0.80 <sup>+0.17</sup> <sub>-0.14</sub>	1.2 <sup>+0.6</sup> <sub>-0.6</sub>	2.51 <sup>+0.41</sup> <sub>-0.38</sub>	2.4 × 10 <sup>35</sup>
2005-06-23 <sup>b</sup>	0.59 <sup>+0.15</sup> <sub>-0.13</sub>	2.4 <sup>+1.6</sup> <sub>-1.6</sub>	2.26 <sup>+0.11</sup> <sub>-0.08</sub>	7.2 × 10 <sup>35</sup>
2005-06-29 <sup>b</sup>	0.78 <sup>+0.19</sup> <sub>-0.19</sub>	1.0 <sup>+0.4</sup> <sub>-0.4</sub>	2.37 <sup>+0.15</sup> <sub>-0.12</sub>	3.3 × 10 <sup>35</sup>
2005-07-07 <sup>b</sup>	0.44 <sup>+0.23</sup> <sub>-0.33</sub>	2.2 <sup>+2.2</sup> <sub>-1.9</sub>	2.41 <sup>+0.07</sup> <sub>-0.03</sub>	5.7 × 10 <sup>35</sup>
2005-07-13 <sup>b</sup>	0.57 <sup>+0.10</sup> <sub>-0.09</sub>	2.2 <sup>+0.9</sup> <sub>-0.8</sub>	2.18 <sup>+0.11</sup> <sub>-0.08</sub>	4.2 × 10 <sup>35</sup>
2005-08-13 <sup>b</sup>	0.68 <sup>+0.24</sup> <sub>-0.19</sub>	0.9 <sup>+0.6</sup> <sub>-0.5</sub>	2.22 <sup>+0.12</sup> <sub>-0.09</sub>	2.0 × 10 <sup>35</sup>
2005-08-28 <sup>b</sup>	0.78 <sup>+0.18</sup> <sub>-0.17</sub>	0.8 <sup>+0.4</sup> <sub>-0.4</sub>	1.94 <sup>+0.16</sup> <sub>-0.05</sub>	1.4 × 10 <sup>35</sup>
State A <sup>c</sup>	0.20 <sup>+0.05</sup> <sub>-0.05</sub>	1.3 <sup>+0.3</sup> <sub>-0.5</sub>	1.93 fixed	5.0 × 10 <sup>32</sup>
State B <sup>d</sup>	0.20 fixed	< 0.3	1.93 fixed	1.5 × 10 <sup>32</sup>

<sup>a</sup>Unabsorbed 0.3–10 keV luminosity at a source distance of 3.5 kpc.

<sup>b</sup>Overall reduced  $\chi^2 = 1.06$  with 1213 degrees of freedom.

<sup>c</sup>Reduced  $\chi^2 = 0.75$  with 16 degrees of freedom.

<sup>d</sup>Reduced  $\chi^2 = 1.38$  with 7 degrees of freedom.

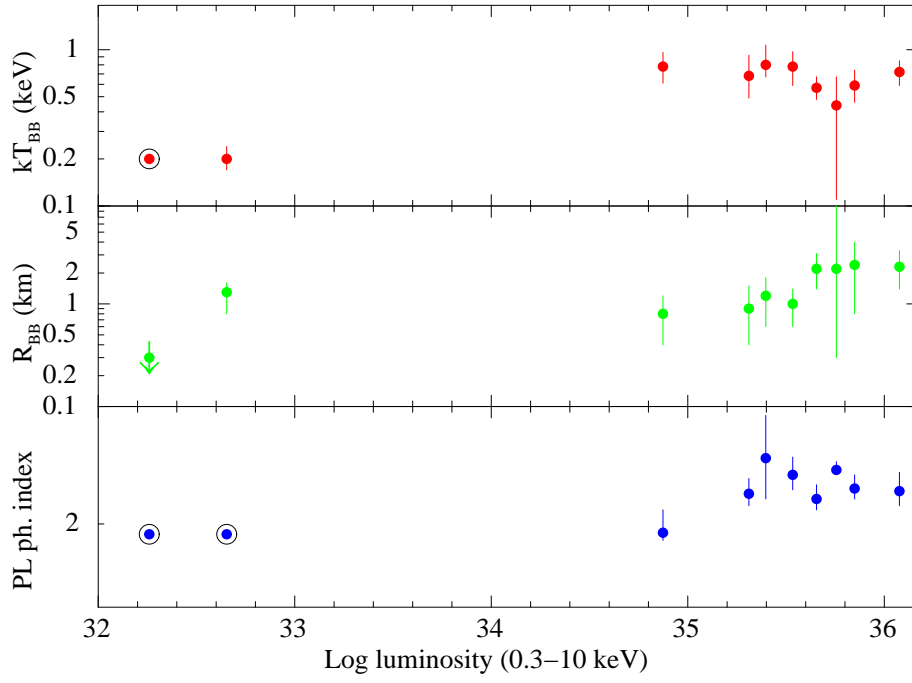


Fig. 3.— Spectral parameters evolution across the outburst. Circled values indicate a fixed parameter in the fitting procedure.



### 3. Discussion and conclusions

SAX J1808 is the prototype of the accreting millisecond X-ray pulsar (AMP) class. The source underwent several outbursts to date which have been monitored in great details thanks to RXTE observations (Wijnands 2005; Wijnands et al. 2003). These observations however were limited to the brightest part of the outburst, being the PCA on RXTE a collimated instrument (and therefore heavily background limited). Here we report on the first campaign aimed at studying the faintest tail of the outburst and return to quiescence. Thanks to the fast repointing and flexible scheduling capabilities of the Swift satellite, we monitored the return to quiescence of SAX J1808 during the 2006 outburst. The bright phase of the outburst is similar to what has been observed in the past: following the peak and the smooth decay a flaring behaviour sets in with at least three rebrightening episodes. After this the source turns to quiescence even if same low level activity (factor of  $\sim 5$ ) is still present.

The puzzling result of this observational campaign on SAX J1808 is that out of 13 observations with luminosity below  $\sim 10^{34}$  erg s $^{-1}$ , 8 times the source was found with a luminosity around  $\sim 5 \times 10^{32}$  erg s $^{-1}$  (see Fig. 1), i.e. at a luminosity level  $\sim 10$  times higher than the true quiescent level (Campana et al. 2002; Heinke et al. 2007). Given the wild luminosity variations this is somewhat strange and calls for the presence of a ‘metastable’ state. This luminosity level is difficult to interpret in case of standard disk accretion but finds a natural explanation if the accretion process is mediated by the magnetic field of the fast spinning neutron star. When the magnetospheric radius (i.e. the radius at which the neutron star magnetic field starts controlling the accretion flow) is larger than the corotation radius, the system is in the (so-called) propeller regime. In this case matter is halted from the rotating magnetosphere and does not accrete onto the neutron star surface (see e.g. Campana & Stella 2000 and references therein). When the magnetospheric radius becomes larger than the light cylinder radius ( $r_{lc} = cP/2\pi$ , where  $c$  is the velocity of light and  $P$  the spin period), the magnetic field cannot corotate any more with the neutron star and a dipole losses will take place. The luminosity range spanned in the propeller regime is  $\sim 440 P_{2.5}^{3/2} M_{1.4}^{-3/2}$  (where  $P_{2.5}$  is the spin period in units of 2.5 ms and  $M_{1.4}$  the neutron star mass in units of  $1.4 M_{\odot}$ ; see Campana & Stella 2000). In order to have the ‘metastable’ state to coincide with the lowest luminosity in the propeller regime (i.e. just before the reactivation of the pulsar), we have to require a magnetic field of  $\sim 7 \times 10^7$  G, in line with previous estimates:  $\sim (1 - 10) \times 10^8$  G using disk-magnetosphere interaction models (Psaltis & Chakrabarty 1999),  $\sim (1 - 6) \times 10^8$  G using simple considerations on the position of the magnetospheric radius during quiescent periods (Di Salvo & Burderi 2003);  $(0.4 - 1.5) \times 10^8$  G modelling period changes during outbursts with a magnetic torque model (Hartman et al. 2008).

The lowest luminosity level in the proposed interpretation is ascribed to the interaction of a turned-on pulsar with the interbinary and circumstellar environment. Variability is expected at this

stage due to the rapidly changing environment as observed, e.g., in the millisecond radio pulsar PSR J1740–5340 (D’Amico et al. 2001; Ferrario et al. 2001) which gets eclipsed over a range of orbital phases for different orbital cycles.

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